## 2.2 EVAPOTRANSPIRATION

The calculation of evapotranspiration (ET) in the South Florida Water Management Model is based on reference crop ET which is adjusted according to crop type, available soil moisture content, and location of the water table. Algorithms used to calculate actual evapotranspiration vary geographically because of different data availability, calibration approaches and varying physical and operational characteristics of different areas within the model domain. For Lake Okeechobee, the pan evaporation method is used to calculate open water and marsh zone ET. In the Everglades Agricultural Area total ET is the sum of its components from the saturated, unsaturated and open water zones. In non-irrigated areas such as the Everglades the unsaturated zone does not exist and total ET is calculated as the sum of open water evaporation and saturated zone (water table) ET. Finally, in irrigated areas in the Lower East Coast, a simple accounting procedure is used to calculate unsaturated zone ET (refer to Sec. 2.2) while saturated and open water ET are calculated based on the Penman-Monteith reference crop ET. In all areas but the lake, the Penman-Monteith method is used to calculate reference crop ET.

### Lake Okeechobee

Evapotranspiration in Lake Okeechobee is calculated daily based on the pan evaporation method, i.e., the reference evapotranspiration (ETR) is equal to the measured pan evaporation ($ET_{pan}$). Although lake ET is predominantly open water ET, spatial variation is accounted for by conceptualizing the lake as made up of three distinct zones (Fig. 2.2.1): an open water zone, a marsh (wetted or inundated littoral) zone, and a no-water (dry littoral) zone. The surface areas of these zones vary with lake stage. ET computation is based on the formula by Shih (1980) modified by Ahn and Ostrovsky (1992). The following equation is used in the model on a daily basis.

$$ET_{LOK,t} = X * ET_{pan,t} (A_{w,t} + k*A_{m,t}) + k * X * ET_{pan,t} * A_{n,t} \tag{2.2.1}$$

where:

$ET_{LOK,t}$ = total LOK evapotranspiration, (ac-ft);
$X$ = pan evaporation coefficient taken as 0.865 (Shih, 1980);
$k$ = evapotranspiration coefficient taken as 1.2 (Shih, 1980);
$A_{w,t}$ = LOK open water surface area, (acre);
$A_{m,t}$ = LOK marsh surface area, (acre);
$A_{n,t}$ = LOK no-water surface area, (acre); and
$ET_{pan,t}$ = historical daily pan evaporation (ft) taken as the average of the readings from the three gaging stations shown in Fig. 2.1.1.

The no-water zone ET is assumed to be limited by the total lake monthly rainfall. Therefore, the total monthly dry littoral zone ET from the lake cannot exceed the total monthly lake rainfall. Daily dry littoral zone ET has a maximum value equal to the product of the total monthly lake rainfall and the ratio of the daily pan evaporation to the total monthly pan evaporation.

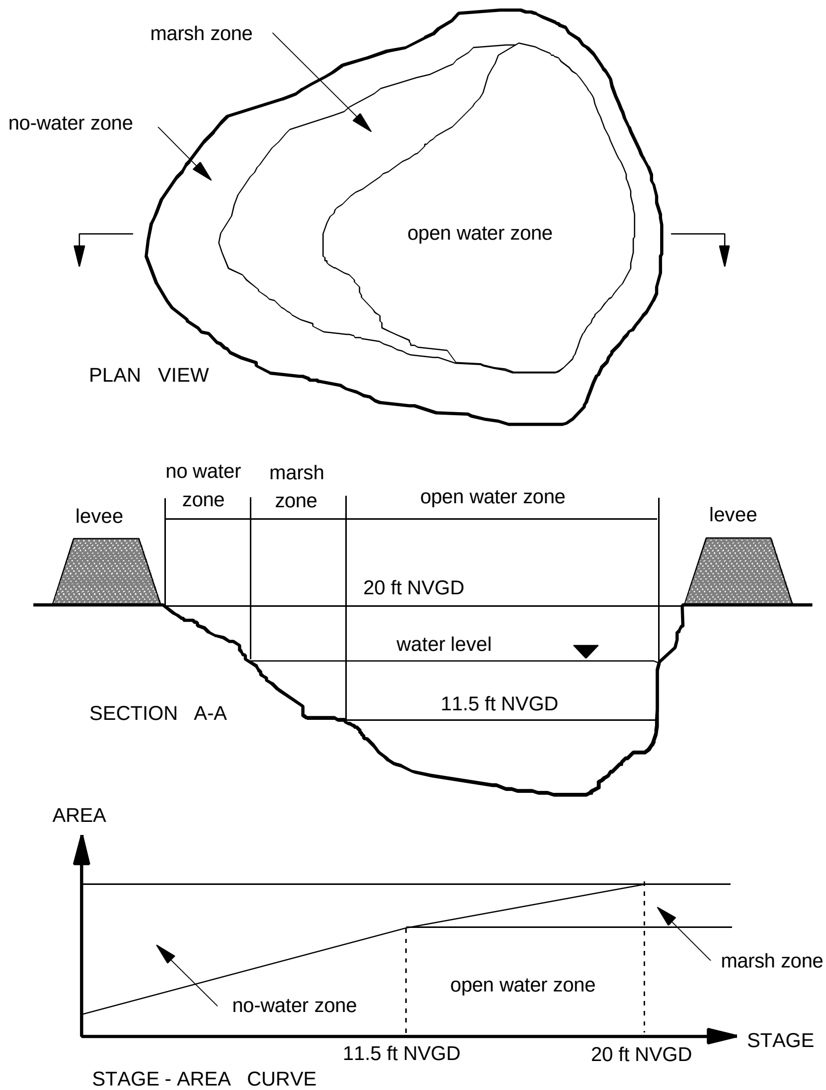


**Figure 2.2.1** Conceptual Representation of the Different Lake Okeechobee Evapotranspiration Zones as Implemented in the South Florida Water Management Model

The marsh zone exists where the bottom elevation of the lake is above 11.5 ft NGVD (Shih, 1980). The following conditional equations conceptualized in Fig. 2.2.1 are used to calculate open water, marsh, and no-water areas, respectively;

$$A_{w,t} = fn(H_t) \quad \text{if } H_t \leq 11.5 \text{ ft NGVD}$$
$$= A_{w,max} \quad \text{otherwise} \tag{2.2.2}$$

$$A_{m,t} = 0 \quad \text{if } H_t \leq 11.5 \text{ ft NGVD}$$
$$= fn(H_t) - A_{w,max} \quad \text{otherwise} \tag{2.2.3}$$

$$A_{n,t} = A_{LOK} - (A_{wt} + A_{mt}) \tag{2.2.4}$$

where:

$H_t$ = stage in Lake Okeechobee at time t, (ft NGVD);
$A_{w,max}$ = Lake Okeechobee open-water surface area at 11.5 ft NGVD or higher, (acres);
$A_{LOK}$ = Lake Okeechobee surface area at 20 ft NGVD or higher, (466,000 acres);
= defines the upper limit of the area enclosed by the peripheral levee around the lake; and
$fn(H_t)$ = stage-area relationship for Lake Okeechobee, defined for stage less than or equal to 11.5 ft.

The rest of the model domain uses the Penman-Monteith evapotranspiration referenced to a dense grass cover of 12 inches in height as recommended by the Food and Agriculture Organization (1990) as the reference ET, i.e., ETR = PET. The Penman-Monteith (P-M) equation is solved on a daily basis using historical (1965-1990) meteorological data (e.g., rainfall, temperature, sky cover and wind speed) from the ten stations shown in Fig. 2.2.2. The P-M equation (Monteith, 1965), in its original form, is given by:

$$\lambda ET_0 = \frac{\Delta(R_n - G) + \rho C_p (e_a - e_d)\frac{1}{r_a}}{\Delta + \gamma\left(1 + \frac{r_c}{r_a}\right)} \qquad (2.2.5)$$

where:

$\lambda ET_0$ = latent heat flux of evaporation, (KJ $m^{-2}$ $s^{-1}$);
$ET_0$ = mass flux of evapotranspiration, (kg $m^{-2}$ $s^{-1}$);
$\lambda$ = latent heat of vaporization, (KJ $kg^{-1}$);
$\Delta$ = slope of vapor pressure curve, (kPa $^oC^{-1}$);
$R_n$ = net radiation flux at surface, (KJ $m^{-2}$ $s^{-1}$);
G = soil heat flux, (KJ $m^{-2}$ $s^{-1}$);
$\rho$ = atmospheric density, (kg $m^{-3}$);
$C_p$ = specific heat of moist air, (KJ $kg^{-1}$ $^oC^{-1}$);
$e_a$ = saturation vapor pressure at surface temperature, (kPa);
$e_d$ = actual ambient vapor pressure at dew point, (kPa);
$(e_a-e_d)$ = vapor pressure deficit, (kPa);
$\gamma$ = psychrometric constant, (kPa $^oC^{-1}$);
$r_c$ = crop canopy resistance, (s $m^{-1}$); and
$r_a$ = aerodynamic resistance, (s $m^{-1}$).

The actual PET assigned to each cell within the model is obtained from a linear interpolation scheme based on the cell's inverse distance from all ten stations (as opposed to the nearest-station method used for assigning daily rainfall values for each cell). The justification for the selected method is that the number of PET stations was not sufficient to avoid abrupt changes in PET values from one cell to the next had the nearest-station method been selected. The equation used to calculate PET for a given grid cell on a specific day is:

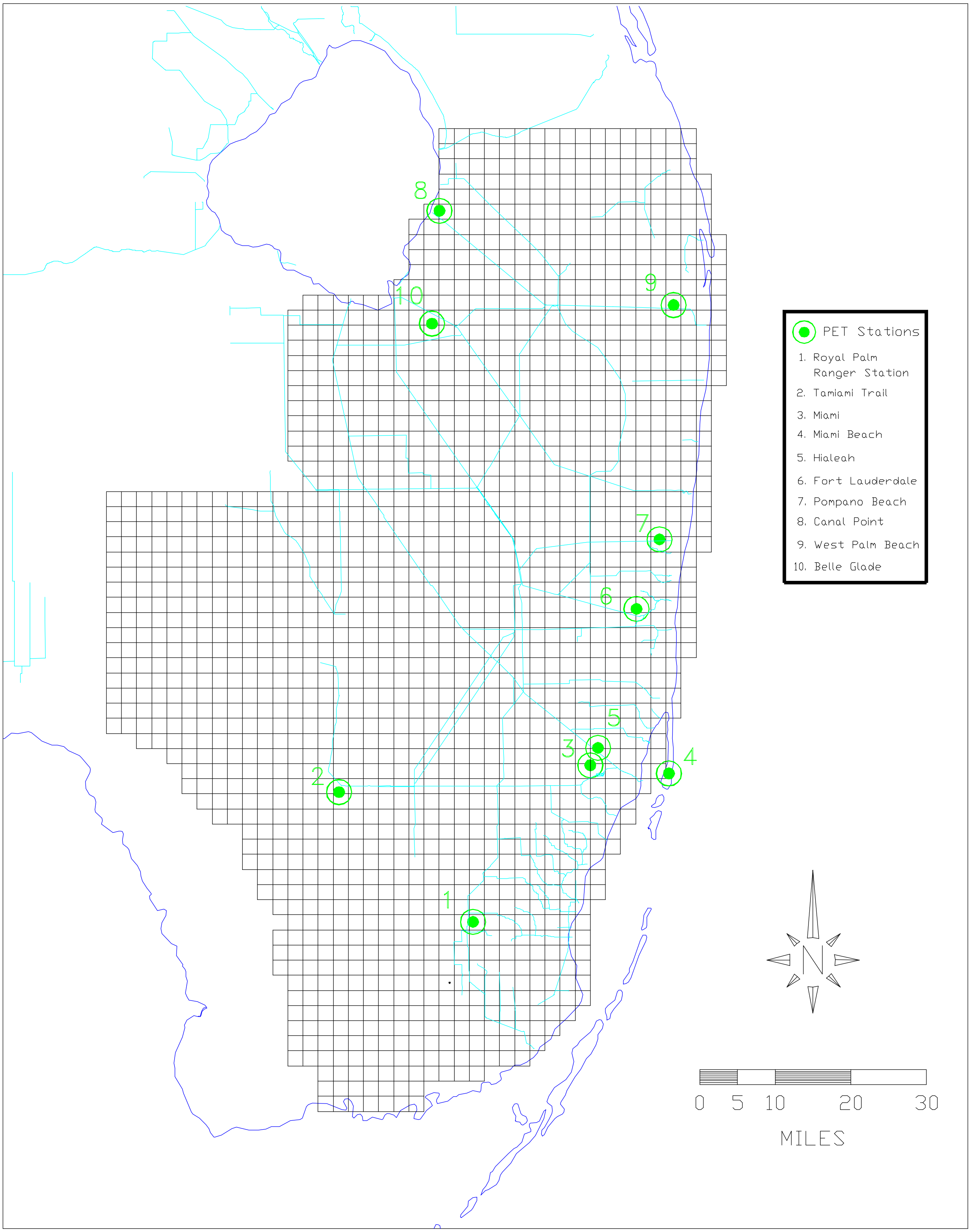


**Figure 2.2.2** Meteorological Stations Used to Calculate Reference ET (Based on the Penman-Monteith Equation) on a Daily Basis as Input to the South Florida Water Management Model

$$PET_{c,j} = \frac{\sum_{i=1}^{10} PET_{i,j}/d_i^{\,n}}{\sum_{i=1}^{10} 1/d_i^{\,n}} \tag{2.2.6}$$

where:

$PET_{c,j}$ = PET at grid cell location c on day j;
$PET_{i,j}$ = PET at station i on day j;
$d_i$ = distance from center of grid cell c to PET station i;
c = grid cell;
i = PET station;
j = day of simulation; and
n = exponent to which distance is raised.

It was determined (Krishnan, 1995) that an exponent of two (n=2) sufficiently spreads the station PET value over the model domain. In addition to the ten daily PET values, the SFWMM reads in ten pre-processed weights (based on the squared inverse distance) for each grid cell.

## Everglades Agricultural Area

The calculation of ET in the EAA is strongly influenced by the operating rules governing the management of the EAA. The details of this topic will be discussed under the Sec. 3.3. The remainder of the model domain, non-LOK and non-EAA, can be partitioned into non-irrigated and irrigated areas. The latter includes an unsaturated zone ET accounting procedure while the former makes simplifying assumptions for the unsaturated zone.

## Non-irrigated Areas

For non-irrigated areas (Water Conservation Areas, Everglades National Park and portions of Big Cypress Preserve) and non-irrigated grid cells in the Lower East Coast, the following assumptions are made: (1) moisture content between land surface and water table does not change; (2) ET comes only from the saturated zone (ETS) and/or ponding (ETP); and (3) infiltration equals percolation.

The generalized form of the ET function in the model is

$$ET = KFACT * ETR \tag{2.2.7}$$

where:

ET = actual evapotranspiration;
KFACT = adjustment factor that takes into account vegetation/crop type and location

of the water table relative to land surface as defined in Table 2.2.1 and Fig. 2.2.3; and

ETR = Penman-Monteith reference crop (turf grass) evapotranspiration.

**Table 2.2.1** Variation of KFACT as a Function of Water Table Location

| **Depth from Land Surface to Water Level**<br>DWT: water table condition, i.e., below ground<br>PND: ponding condition, i.e., above ground | **Adjustment Factor (KFACT)** |
|---|---|
| DWT ≥ DDRZ | 0.0 |
| DSRZ < DWT < DDRZ | [(DDRZ-DWT)÷(DDRZ-DSRZ)] * KVEG |
| 0 ≤ DWT ≤ DSRZ | KVEG |
| 0 < PND ≤ OWPOND | KVEG + (KMAX-KVEG)*PND÷OWPOND |
| PND > OWPOND | KMAX |

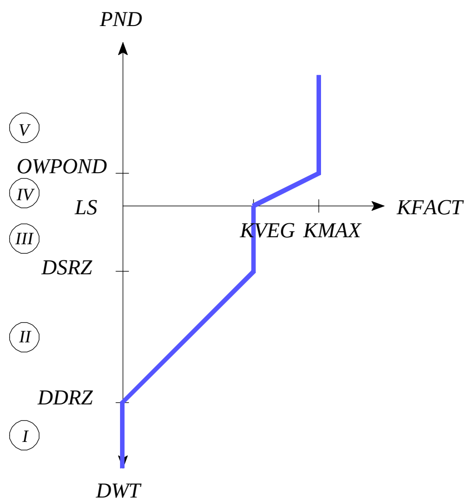


**Figure 2.2.3** KFACT as a Function of Water Table Location

The definition of the variables used in Fig. 2.2.3 is as follows: *OWPOND* = minimum ponding depth above which ET for open-water is assumed, e.g., plants are fully submerged such that transpiration no longer contributes to ET; *LS* = land surface; *DSRZ* = depth from land surface to the bottom of the shallow root zone; *DDRZ* = depth from land surface to the bottom of the deep root zone; *PND* = depth from land to top of ponding; *DWT* = depth from land surface to water table; *KVEG* = vegetation / crop coefficient which is interpolated based on mid-month values assigned for each land use; *KMAX* = coefficient applied to ET for open water condition. (note: KMAX is equal to 1.0 for wetlands and 1.1 elsewhere.)

Tables 2.2.2 and 2.2.3 show the fourteen land use classifications used in the model with the associated ET parameters. Note that:

**1.** Land use 7 through 9, and 10 pertain to the three EAA agricultural types and Stormwater Treatment Area wetland classification, respectively;

**2.** Land use 3, 4, 5, 6, 12 and 13 are land use types consistent with the Natural System Model (NSM) land use classification scheme; and

**3.** KVEG values for the three land uses in the EAA (LU7, LU8 and LU9) are the product of two parameters in the model: (a) theoretical KVEG values which are coefficients obtained from a field-scale study of ET in the EAA (Abtew and Khanal, 1992); and (b) adjustment factors used to convert theoretical KVEG from field-scale to regional-scale. The appropriate adjustment factors were determined during the calibration of the EAA (refer to Sec. 6.1).

**Table 2.2.2** Static ET Parameters Used in the South Florida Water Management Model

| Land Use Type | OWPOND | KMAX | DSRZ | DDRZ |
|---|---|---|---|---|
| LU1: Low-density Urban | 1.0 | 1.1 | 1.0 | 2.0 |
| LU2: Agricultural | 1.0 | 1.1 | 2.0 | 3.0 |
| LU3: Fresh Marsh | 3.0 | 1.0 | 0.0 | 1.5 |
| LU4: Sawgrass | 3.0 | 1.0 | 0.0 | 3.0 |
| LU5: Wet Prairie | 3.0 | 1.0 | 0.0 | 5.7 |
| LU6: Scrub and Shrub | 3.0 | 1.0 | 0.0 | 4.0 |
| LU7: Truck Crops | 1.0 | 1.1 | 1.5 | 3.0 |
| LU8: Sugar Cane | 3.0 | 1.1 | 1.5 | 3.83 |
| LU9: Irrigated Pasture | 1.0 | 1.1 | 1.5 | 3.0 |
| LU10: STA Wetland | 3.0 | 1.1 | 0.5 | 4.5 |
| LU11: High-Density Urban | 1.0 | 1.1 | 1.0 | 1.5 |
| LU12: Forest | 3.0 | 1.0 | 0.0 | 9.5 |
| LU13: Mangrove | 3.0 | 1.0 | 0.0 | 0.3 |
| LU14: Melaleuca | 10.0 | 1.1 | 1.5 | 3.0 |

For accounting purposes, if the water level goes above land surface (LS), the evapotranspiration is referred to as open-water ET (ETP). ETP is limited by the available ponding for the current day, i.e., previous day ponding plus current day rainfall. The portion of ET calculated from Eq. (2.2.7) in excess of available ponding for the day is assumed to come from the saturated zone (ETS).

**Table 2.2.3** Calibrated Vegetation/Crop Coefficient (KVEG) as a Function of Land Use and Month as Implemented in the South Florida Water Management Model

| | LU1 | LU2 | LU3 | LU4 | LU5 | LU6 | LU7 | LU8 | LU9 | LU10 | LU11 | LU12 | LU13 | LU14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| JAN | 0.626 | 0.701 | 0.725 | 0.655 | 0.813 | 0.805 | 0.363 | 0.454 | 0.369 | 0.802 | 0.323 | 0.693 | 0.741 | 0.800 |
| FEB | 0.762 | 0.693 | 0.902 | 0.770 | 0.952 | 0.962 | 0.414 | 0.360 | 0.420 | 0.962 | 0.381 | 0.762 | 0.920 | 0.770 |
| MAR | 0.744 | 0.610 | 0.920 | 0.820 | 0.951 | 0.970 | 0.696 | 0.440 | 0.600 | 0.970 | 0.372 | 0.778 | 1.000 | 0.850 |
| APR | 0.722 | 0.542 | 0.901 | 0.760 | 0.933 | 0.955 | 0.627 | 0.528 | 0.627 | 0.955 | 0.361 | 0.773 | 0.935 | 0.880 |
| MAY | 0.742 | 0.661 | 0.755 | 0.642 | 0.893 | 0.805 | 0.685 | 0.757 | 0.757 | 0.823 | 0.372 | 0.743 | 0.772 | 0.910 |
| JUN | 0.742 | 0.710 | 0.675 | 0.638 | 0.881 | 0.751 | 0.652 | 0.988 | 0.968 | 0.751 | 0.372 | 0.644 | 0.692 | 0.900 |
| JUL | 0.788 | 0.744 | 0.771 | 0.642 | 0.977 | 0.871 | 0.436 | 0.751 | 0.701 | 0.851 | 0.394 | 0.745 | 0.782 | 0.910 |
| AUG | 0.886 | 0.810 | 0.805 | 0.654 | 1.005 | 0.941 | 0.429 | 0.683 | 0.637 | 0.941 | 0.443 | 0.800 | 0.894 | 0.970 |
| SEP | 0.842 | 0.822 | 0.811 | 0.670 | 1.010 | 0.961 | 0.454 | 0.672 | 0.602 | 0.962 | 0.421 | 0.830 | 0.900 | 0.970 |
| OCT | 0.906 | 0.702 | 0.802 | 0.660 | 0.990 | 0.882 | 0.387 | 0.445 | 0.356 | 0.892 | 0.453 | 0.830 | 0.844 | 0.860 |
| NOV | 0.804 | 0.723 | 0.724 | 0.645 | 0.921 | 0.824 | 0.476 | 0.486 | 0.445 | 0.804 | 0.402 | 0.771 | 0.723 | 0.880 |
| DEC | 0.722 | 0.700 | 0.731 | 0.647 | 0.794 | 0.811 | 0.503 | 0.515 | 0.372 | 0.811 | 0.361 | 0.714 | 0.743 | 0.800 |

## Irrigated Areas in the Lower East Coast

For irrigated areas, primarily LEC Service Area grid cells, the unsaturated zone is treated as a separate control volume where infiltration, percolation, evapotranspiration and changes in soil moisture are accounted for. The reasons for the unsaturated zone accounting are: (1) the desire to implement the Water Shortage Plan in the LEC (SFWMD, 1991) which entails cutbacks in irrigation amounts and frequencies; (2) the need to quantify LEC irrigation applied to the unsaturated zone; and, consequently, (3) the need to more accurately assess changes in irrigation requirements associated with changes in land use. Supply-side management (refer to Sec. 3.2) for the Lake Okeechobee Service Area is the counterpart of the LEC Shortage plan (refer to Sec. 3.5) for the Lower East Coast of South Florida.

In irrigated areas in the LEC, a two-step approach is taken to calculate total ET from each irrigated grid cell. In the first step, unsaturated zone moisture accounting is performed for the irrigated portion of a model grid cell. The water balance equation for the unsaturated zone is:

$$\Delta S = NIRRSUPTOT - ETU + INFILT - PERC. \qquad (2.2.8)$$

NIRRSUPTOT, and ETU represent the preprocessed (input to the model) total net irrigation supply and unsaturated zone evapotranspiration. They are calculated from the ET-Recharge model (Restrepo and Giddings, 1994).

Infiltration depth, INFILT, is the minimum of ponding depth, infiltration rate, and available unsaturated zone storage. Therefore, the time-dependent moisture content in the unsaturated zone ($S_t$) can be expressed as;

$$S_t = S_{t-1} + INFILT + NIRRSUPTOT - ETU. \qquad (2.2.9)$$

If $S_t$ is less than the water-holding capacity of the unsaturated zone, SWSCAP, then percolation, PERC, is zero. Otherwise, PERC becomes the soil-moiture content in exceess SWSCAP and the final moisture-content for time step t equals SWSCAP.

In the second step, the saturated zone evapotranspiration (ETS) is calculated using ET from the generalized ET function, Eq. (2.2.7):

$$ETS = ET - ETU. \qquad (2.2.10)$$

Due to differences in scale and assumptions used between the ET-Recharge model and SFWMM, there are instances when the unsaturated zone moisture accounting cannot be carried out due to the lack (or absence) of moisture in the unsaturated zone. In such cases, the unaccounted for ETU is taken directly out of the saturated zone, thus lowering the water table by a corresponding amount.

**ET-Recharge Model.** In the LEC service areas (Fig. 1.3.5), irrigation supply and unsaturated zone ET are pre-processed, i.e., pre-calculated quantities, input to SFWMM, and used in the unsaturated zone moisture accounting. These quantities, among others, were output from the ET-Recharge model (Giddings and Restrepo, 1995). This model was originally used to provide a more accurate method for estimating the recharge component for the District's countywide groundwater models. The model was later enhanced to handle any user-specified model grid, e.g., SFWMM grid system.

The necessary input to the model can be classified into two categories:

**1.** a description of a basic element area (BEA): area; levels 1, 2, and 3 land use codes; soil code equivalent to AFSIRS SOIL.DAT file; cell (row and column numbers) location within the SFWMM grid system; vertical hydraulic conductivity of the soil; active/inactive designation for cell; ET station basin designation; and

**2.** a reference table for each BEA in (1) relating the District's level 3 land use classification to the following: runoff coefficients; crop type; growing season; percent pervious area; switch indicating if a BEA is irrigated or not; and irrigation system efficiency.

To perform a crop root zone water balance on a daily basis, a two-step approach is taken.

First, basic element areas (BEAs) are defined for the LEC. By definition, a BEA is a polygon having a unique combination of attributes such as land use, soil type, percent irrigated, non-irrigated and impervious area, vertical hydraulic conductivity, and SFWMM cell location. The size of a SFWMM grid cell is the upper limit on the size of a BEA.

Second, if a BEA falls within a pervious area the Agricultural Field-Scale Irrigation Requirements Simulation (AFSIRS) program (Smajstrla, 1990) is called to perform crop root zone water balance on a daily basis. AFSIRS calculates irrigation requirements and crop evapotranspiration rates as a function of crop type, soil type, irrigation system, growing season, and climatic conditions. It assumes that crop requirements are met from the unsaturated zone through rainfall or supplemental irrigation. An irrigation management option within AFSIRS was selected such that the exact amount and timing of the irrigation is to be used to restore the root zone to field capacity (i.e., maximum yield and thus, maximum or potential ET is always maintained).

Some of the most important assumptions in AFSIRS are listed below:

**1.** The calculated drainage does not distinguish between runoff and percolation.

**2.** Crop root zone is entirely in the unsaturated zone.

**3.** Lateral flow is neglected in the unsaturated zone.

**4.** Crop requirements are met from the unsaturated zone through rainfall or supplemental irrigation.

**5.** Crop-water requirements are calculated based on maximum yield.

**6.** AFSIRS does not compute yield but calculate the quantity and frequency of irrigation necessary to avoid crop stress.

**7.** The calculated net irrigation requirement does not include leaching, freeze protection or crop cooling requirements.

Daily rainfall, and reference crop ET (ETR) are defined as inputs to AFSIRS. Since rainfall amounts are defined for each SFWMM grid cell, RF for a basic element area is taken as the value assigned to the SFWMM cell where the BEA is located. Daily ETR, on the other hand, is calculated using the Penman-Monteith (P-M) equation from within the ET-Recharge model. To minimize data needs to solve this equation (2.2.5), the more significant variables, i.e., specific to South Florida conditions, were identified and an approximate P-M equation was developed leading to a modified Penman-Monteith method (Restrepo and Giddings, 1994). ETR is solved for 10 distinct locations within the SFWMM model domain which represent meteorological stations (Fig. 2.2.2). The ETR for each basic element area represents the distance-weighted sum of the ETR values measured at the ten stations. AFSIRS calculates the potential evapotranspiration for crop c (ETc) using the formula:

$$ETc = kc * ETR \tag{2.2.11}$$

where kc is the crop coefficient that varies with crop type and crop growth stage.

The rate at which water is returned from the soil to the atmosphere by evapotranspiration is controlled by two factors: atmospheric demand and soil-water availability (Jensen, et al., 1990). In AFSIRS, the water balance equation for the crop root zone is:

$$\Delta STO = RAIN + NIRR - DRAIN0 - RUNOFF - ET \tag{2.2.12}$$

where:

$\Delta$STO = change in root zone soil water storage;
RAIN = rainfall;
NIRR = net irrigation requirement or irrigation supply used as input to SFWMM;
DRAIN0 = drainage;
RUNOFF = surface runoff; and
ET = evapotranspiration.

In the ET-Recharge model, the runoff and drainage terms are combined to form the variable DRAIN, i.e., RUNOFF + DRAIN0. All BEAs within a SFWMM grid cell can be combined and Eq. (2.2.12) can be rearranged and written for a SFWMM grid cell as:

$$NIRR = \Delta STO - RAIN + DRAIN + ET \tag{2.2.13}$$

Drainage is calculated as the difference between rainfall and available soil water storage (storage beyond field capacity) at the time rain occurs. By implementing an extended form of the Soil Conservation Service (SCS) runoff estimation method (McCuen, 1982), the DRAIN term can be partitioned back into total direct runoff and the original drainage term DRAIN0 in Eq. (2.2.12) (Giddings and Restrepo, 1995). AFSIRS assumes that the crop root zone is entirely within the unsaturated zone (ET = ETU). The maximum unsaturated zone ET, ETUmax, can vary depending on whether a BEA is impervious or pervious.

For impervious areas, the ET-Recharge model assumes negligible ETUmax. For SFWMM grid cells with non-irrigated pervious areas, ETUmax = ETc*% of pervious area. For SFWMM grid cells with irrigated pervious areas, ETUmax = (ETc - supplemental requirement)*% of pervious area, i.e., ETUmax is limited by the amount of available soil moisture in the unsaturated zone. Supplemental irrigation requirements can be met from the water table.

The ET-Recharge model aggregates output from BEAs to SFWMM grid values. A list of output information generated on a daily basis from the model pertinent to the SFWMM is as follows:

**1.** composite crop PET per model grid cell ($ET_{p\_cell}$);
**2.** unsaturated zone ET per model grid cell ($ETU_{cell}$);
**3.** unsaturated zone ET for irrigated portion of each model grid cell ($ETIU_{cell}$); and
**4.** irrigation deliveries per use type.

Irrigation deliveries calculated from the ET-Recharge model are treated as target irrigation demands in the SFWMM and are met from the water table; they are the basis for implementing the LEC trigger and cutback modules.